RELATIONSHIP OF TROPOPAUSE AND JET STREAMS TO RAINFALL IN SOUTHEASTERN UNITED STATES, FEBRUARY 4-9, 1957

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1. INTRODUCTION

During the period February 4–9, 1957 persistent rains (fig. 1) occurred in the southeastern portion of the United States associated with weak wave formation on a quasi-stationary front (fig. 2) with no significant cyclone developments in the area. This paper investigates the relationship of this marked precipitation area to the tropopause break zone and jets. The investigation is made by means of a revised type of tropopause chart and a new chart, the jet level winds aloft chart, that have been routinely prepared at the National Weather Analysis Center (NAWAC) since February 1957. For convenience of study the information from the tropopause charts and jet level winds aloft charts, which give the maximum wind between 25,000 and 55,000 feet, is combined in vertical cross sections.

Although analyzed charts during February exhibited a seemingly anomalous behavior with regard to the relationship between the tropopause interruption or break-zone and the jet stream, this investigation shows that the relationship during February 4–9 was in many respects similar to the classical picture.

2. SYNOPTIC SITUATION

A cold front extending from the Middle Atlantic States through northern and western Texas at 1230 GMT, February 4, 1957 (fig. 3A) moved slowly southward thereafter, becoming nearly stationary through the South Atlantic and Gulf States by 1230 GMT, February 5. The front remained in the same general area until the morning of February 8 with numerous weak waves, only one of which developed into a deepening low center off the North Carolina coast on February 6, moving east-northeastward thereafter. A wave, gradually developing on the eastern slope of the central Rockies during February 8, moved east-northeastward, with the front in advance becoming warm and moving northward to north of the Ohio River. This wave and another wave development off the North Carolina coast on February 9 consolidated into a deepening Low in New England by 0030 GMT, February 10, with the front again moving southward as a cold front into the South Atlantic and Gulf States by 1230 GMT, February 10. Figures 3A, 4A, and 5A show the surface weather maps for 1230 GMT, February 4, 7, and 9 and figure 2 is a

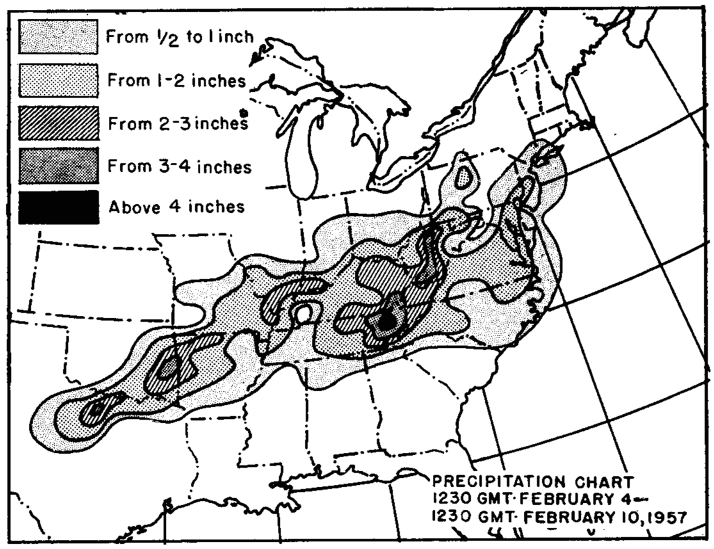

FIGURE 1.—Approximate total accumulated precipitation for the period 1230 GMT, February 4 through 1230 GMT, February 10, 1957.

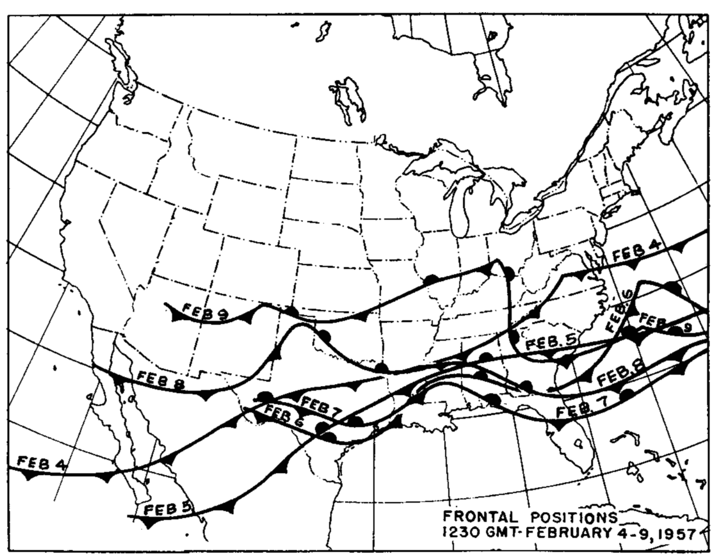

FIGURE 2.—Composite showing successive positions of fronts in southeastern United States for 1230 GMT, February 4–9, 1957.

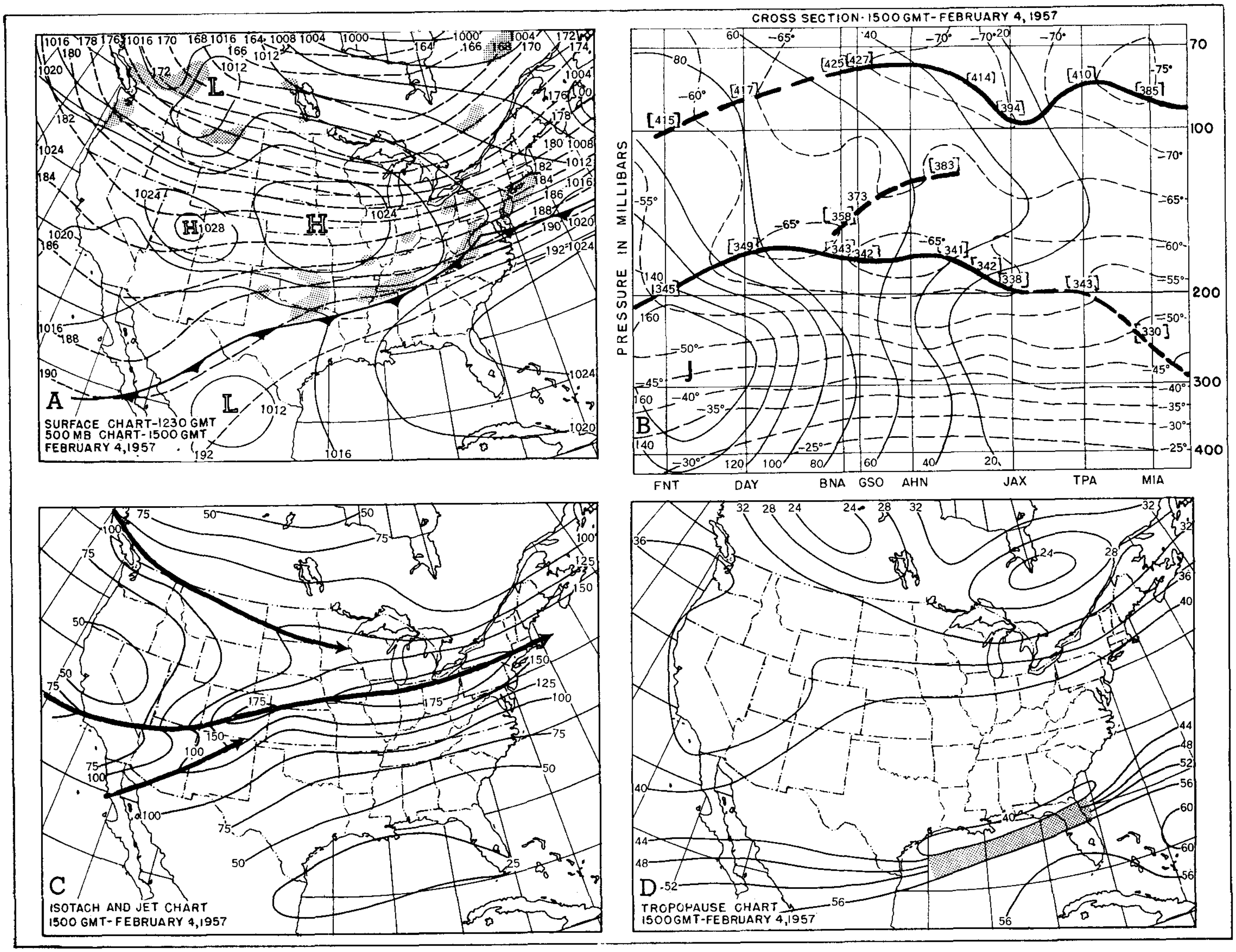

FIGURE 3.—(A) Surface map for 1230 GMT February 4, 1957, with 500-mb. contours (dashed lines) for 1500 GMT superimposed. Contours at 200-foot intervals are labeled in hundreds of feet. Stippled areas indicate current precipitation. (B) Vertical cross section above 400 mb., Flint, Mich. to Miami, Fla., for 1500 GMT February 4, 1957. Thin solid lines are isotachs at 20-knot intervals; thin dashed lines, temperature in degrees C.; heavy solid lines, tropopause; heavy dashed lines, inversions or significant stabilization levels with potential temperatures in brackets. Large "J" shows position of jet core. FNT=Flint, Mich., DAY=Dayton, Ohio, BNA=Nashville, Tenn., GSO=Greensboro, N. C., AHN=Athens, Ga., JAX=Jacksonville, Fla., TPA=Tampa, Fla., and MIA=Miami, Fla. (C) Isotach and jet stream analysis for 1500 GMT, February 4, 1957 based on jet level winds aloft chart and 300-, 200- and 150-mb. analyzed charts. Isotachs at 25-knot intervals are thin solid lines and jet streams are shown by heavy solid arrows. (D) Tropopause chart for 1500 GMT, February 4, 1957. Tropopause height contours are labeled in thousands of feet and indicated break zone is shaded.

composite giving the 1230 GMT frontal positions for February 4 through 9.

Superimposed on the surface maps in figures 3A, 4A, and 5A are the 500-mb. contours for 1500 GMT of the same days. Throughout the period February 4–9, a broad trough covered most of the United States with strong zonal flow prevailing and the winds remained predominantly from west-southwest to west in the precipitation area.

Considering the lack of wave development on the front and the zonal character of the 500-mb. flow, the precipitation (fig. 1) was quite marked in areal extent and

TABLE 1.—*Daily precipitation (inches) February 5–10, at selected stations, for 24-hour periods ending at 0730 EST. (Data provided by River Services Section.)*

Station	February 1957						Total precipitation
	5	6	7	8	9	10	
Ft. Smith, Ark	1.79	0.37	T	1.41	------	------	3.57
Lexington, Ky	.10	.23	0.01	.10	0.64	0.97	2.05
Flattop, W. Va	.08	.80	.28	.37	1.12	.47	3.21
Knoxville, Tenn	.36	.42	.42	1.43	1.09	.28	4.00
Richmond, Va	T	.11	.17	.27	.39	.31	1.25
Paducah, Ky	.33	.25	.02	.29	.11	.13	1.13
Bowling Green, Ky	.37	.25	T	.28	.41	.39	1.70
Nashville, Tenn	.13	.06	.33	.54	.24	.37	1.67

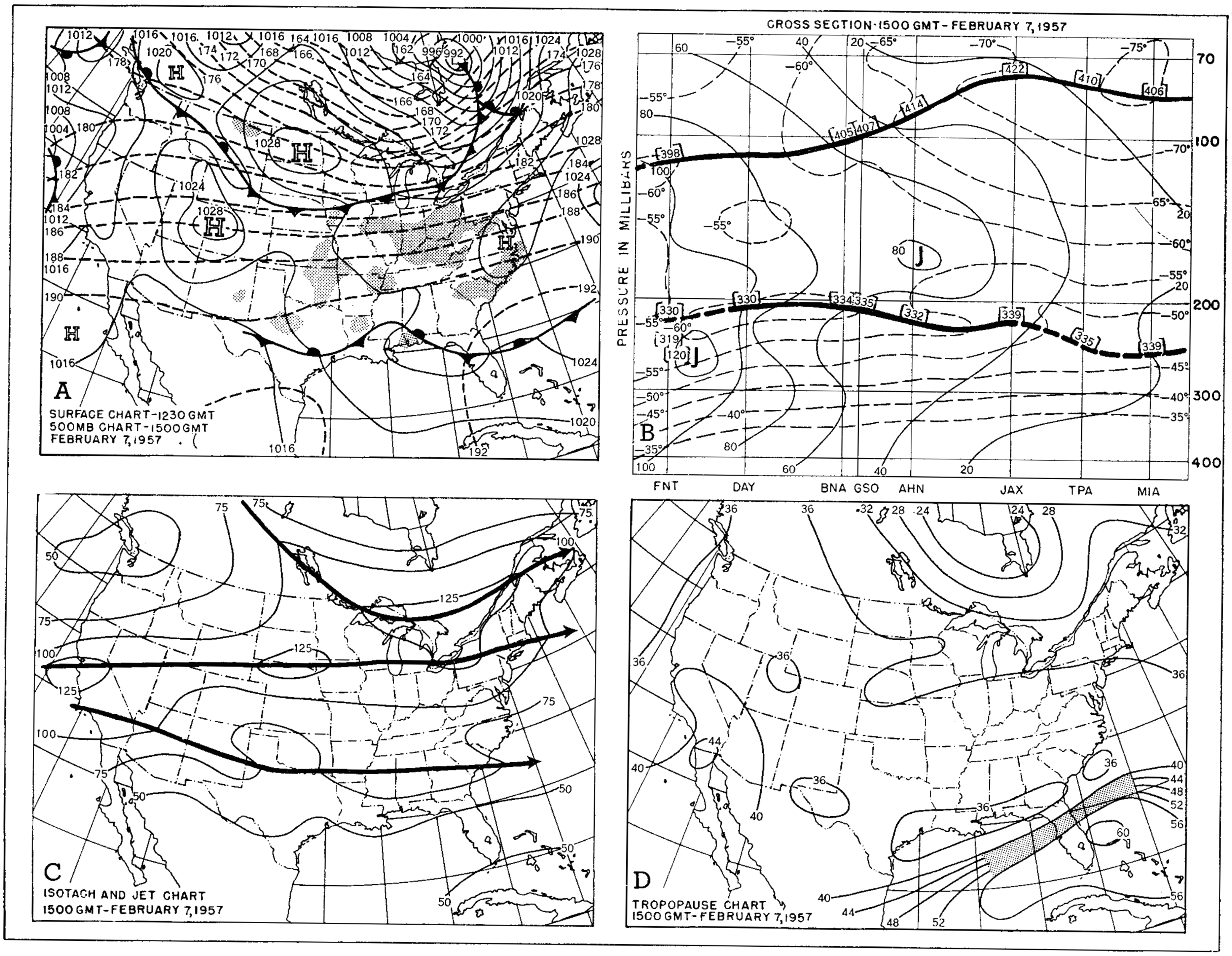

FIGURE 4.—(A) Surface map (with precipitation areas stippled) for 1230 GMT, February 7, 1957, with 500-mb. contours (dashed lines) for 1500 GMT superimposed. (B) Vertical cross section, Flint to Miami, 1500 GMT, February 7. (C) Isotach and jet stream analysis, 1500 GMT, February 7. (D) Tropopause height chart, 1500 GMT, February 7.

quantity. The area of 1.00 inch or more for the period extended quite uniformly from north-central Texas to the Middle Atlantic States, with rather erratic occurrence of heavier totals within the area. Table 1 shows the daily precipitation at selected stations throughout the area. Generally, stations in the western section of the region received most or all of their rain toward the beginning of the period, those in the eastern section toward the end of this period. Most stations in the central portion of the area had rain on each day of the period.

3. TROPOPAUSE CHARTS

Simply stated, the tropopause separates the troposphere from the stratosphere. Saucier [1] defines it as follows: "The tropopause marks a change in the vertical temperature lapse rate from rather large values in the upper troposphere to relatively small or even negative values in the lower stratosphere." Many investigators, however, have demonstrated that the tropopause is often not a single surface but exists as a multiple tropopause or layer appearing in vertical cross sections as an overlapping leaflike structure [2].

For purposes of analysis of the tropopause NAWAC has used the following definition of the "first tropopause": "The 'first tropopause' is defined as the lowest level at which the lapse-rate decreases to 2° C./km. or less, and averages 2° C./km. or less for at least 2 km. above. In addition . . . the lowest tropopause must satisfy both of the following conditions: (a) It must occur between the 600 and 30 mb. levels, and (b) its temperature must be colder than −30° C." [3]. This definition is applied ". . . so as to exclude the bases of frontal and other tropospheric stable layers." At NAWAC, methods of analysis were simplified as of February 1, 1957. Heights

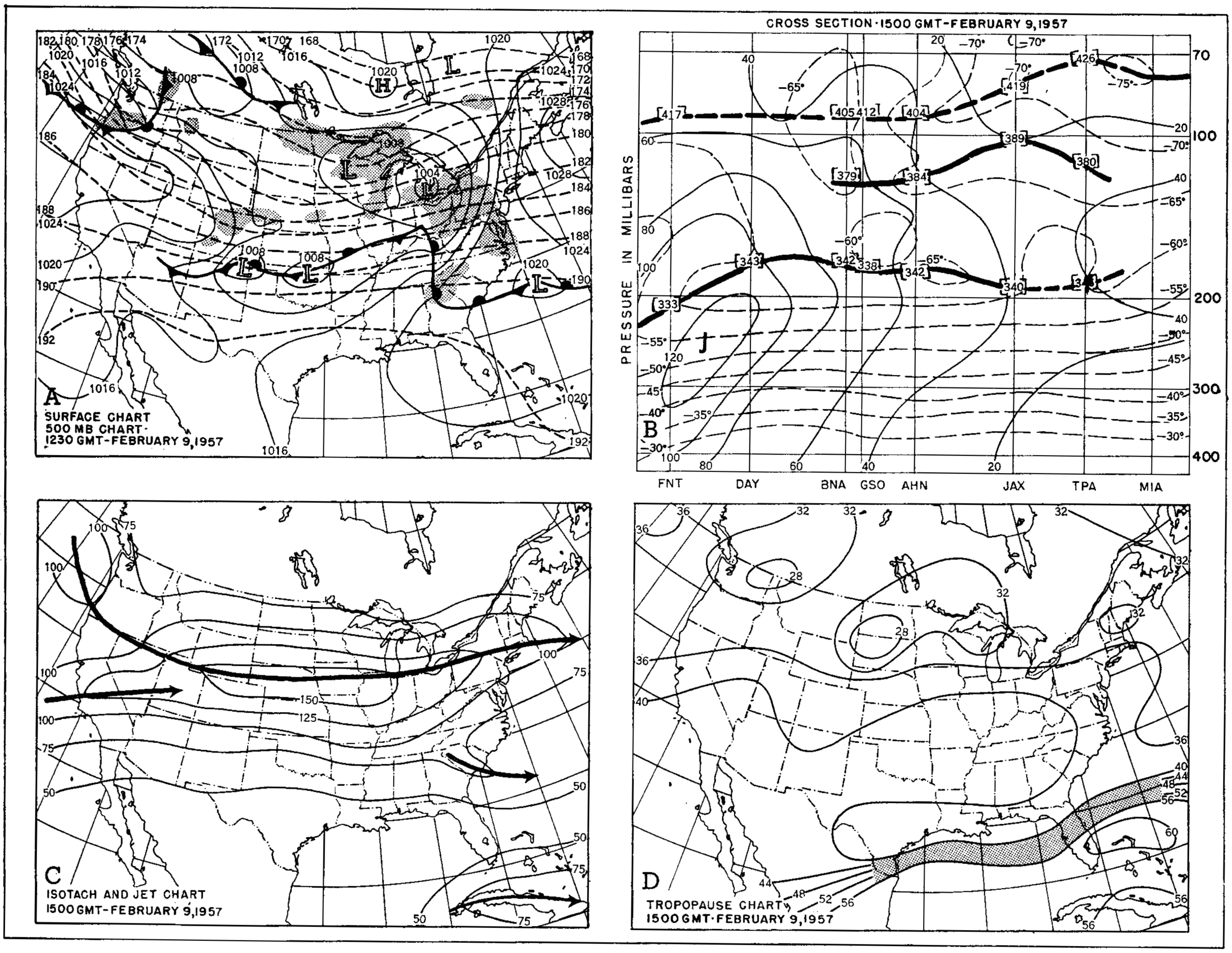

Figure 5.—(A) Surface map (with precipitation areas stippled) for 1230 GMT, February 9, 1957 with 500-mb. contours (dashed lines) for 1500 GMT, superimposed. (B) Vertical cross section, Flint to Miami, 1500 GMT, February 9. (C) Isotach and jet stream analysis, 1500 GMT, February 9. (D) Tropopause height chart, 1500 GMT, February 9.

of the tropopause are plotted as pressure heights in hundreds of geopotential feet and contour isopleths at 4000-foot intervals with 40,000 feet as a base are drawn. Tropopause interruptions or breaks were formerly shown as discontinuities of the height isopleths. The following convention has been substituted: When three or more contours are crowded so close that two adjacent contours are closer than ½° of latitude over a zone of 10° of longitude or more long, a shaded zone is indicated. The two bounding contours are shown continuously with intermediate contours discontinued at the inflow side and resumed at the outflow side of the zone.

Tropopause charts for 0300 and 1500 GMT, February 4–9 were examined for the purposes of this study and those for 1500 GMT of February 4, 7, and 9 are reproduced in figures 3D, 4D, and 5D. These exhibit a considerable uniformity through the precipitation area under consideration, with a break zone present through the northern Gulf of Mexico and northern Florida and an elongated area of comparatively low tropopause heights just to the north. An area of relatively steep gradient of tropopause height oscillated from the Great Lakes region to north of the Lakes and then southward again over the Lakes during the period. However, this latter area did not meet the criteria for shading as a break zone. Of the soundings to the north of Flint, Mich., only the data at Moosonee, Ontario, suggested a slight possibility for a double tropopause or leafing structure, but the evidence was not conclusive enough definitely to establish a lower-level tropopause and, therefore, a break zone. The area between these zones maintained a relatively flat topography of tropopause heights.

4. JET STREAM CHARTS

A new chart, routinely prepared at NAWAC and transmitted by facsimile beginning February 1, 1957, is called the Jet Level Winds Aloft Chart. On this chart are plotted the winds at 30,000, 40,000, and 50,000 feet and the maximum wind and height, if at some other level between 25,000 and 55,000 feet. At first glance, it would seem easy to determine the positions of the jet streams from this chart. In actual practice, short runs at many stations, precluding the reporting of the actual maximum wind between 25,000 and 55,000 feet, may result in an inaccurate isotach and jet analysis if this chart is used alone. Therefore, jet stream charts have been prepared synthesizing information contained on the jet level winds aloft chart and on the 300-, 200-, and 150-mb. charts. Figures 3C, 4C, and 5C show three of these jet stream charts. The salient feature indicated by the jet stream analyses was the weakening of the strong jet passing just south of the Great Lakes at the beginning of the period, as a subsidiary jet became more pronounced through the southern States by the middle of the period. Subsequently, the northern jet again strengthened as the southern one weakened.

5. CROSS SECTIONS

A series of high-level cross sections for 1500 GMT for the period February 4–9 was prepared and three of these are reproduced in figures 3B, 4B, and 5B. The chosen cross section, from Flint to Miami, was nearly perpendicular to the high-level wind flow throughout the period, obviating the problem of computing components of wind perpendicular to the cross section. These cross sections give a three-dimensional representation of the information contained on the tropopause charts and the jet stream charts, and therefore furnish a convenient tool for study of these high-level features.

The most striking feature of the cross section for 1500 GMT, February 4, 1957 (fig. 3B), is the strong jet core near Flint, Mich. at 30,000–35,000 feet. The tropopause that was present above this jet core extended as far south as the Athens, Ga. area, gradually weakened southward to Jacksonville, Fla., and existed only as an inversion, not meeting the arbitrary tropopause criteria, between Jacksonville and Miami. The synoptic tropopause chart (fig. 3D), as described earlier, showed an area of comparatively lower tropopause height to the north of the Great Lakes. Although the gradient of tropopause height in this area was quite steep, the presence of a break in the tropopause could not be deduced from the evidence available. However, the lower tropopause to the north and the higher tropopause to the south of the jet core did approach the classical picture of Palmén [4]. Another distinct but higher-level tropopause extended from Miami to Jacksonville continuing northward and overlapping the first tropopause as far north as the area between Nashville, Tenn. and Greensboro, N. C., north of which it degenerated into an inversion not meeting the requirements for tropopause identification. The shaded break zone analyzed on the tropopause chart (fig. 3D) is in the area where the lower tropopause fades out and the upper tropopause becomes the predominant one. To conform to the typical picture of Palmén one might expect to find another jet core between the overlapping tropopause leaves. The cross section does show a secondary wind maximum between the tropopauses but, perhaps because of the absence of wind reports in the Nashville-Greensboro area, a jet core cannot be definitely established. The synoptic jet stream chart (fig. 3C) indicates a subsidiary jet stream in the far southwest, becoming masked by the much stronger jet stream to its north in the central portion of the United States and possibly reappearing in the Virginia-North Carolina coastal area. This jet was analyzed on the NAWAC transmitted 150-mb. chart for 1500 GMT, February 4.

During the period following February 4 the strong jet core near Flint weakened somewhat with the maximum wind speed decreasing gradually from a value in excess of 175 knots to one near 120 knots. During the same period the higher-level subsidiary wind maximum in the area from Nashville to Athens gradually increased until at 1500 GMT, February 7 a definite jet core of more than 85 knots appeared between 40,000 and 45,000 feet over Athens (fig. 4B). The composite jet stream chart for this time confirms the presence of this jet stream through the Southern States from the west coast to the east coast (fig. 4C). The high-level tropopause through the southern part of the cross section was relatively unchanged, but by February 7 there appeared to be definite evidence of its northward extension as far as Flint (fig. 4B). The lower-level tropopause also changed little between Jacksonville and Dayton but the difference in potential temperature of the tropopause levels at Dayton and Flint suggests the possibility of a minor tropopause break near the jet core between Dayton and Flint. However, the slight difference in potential temperature of the tropopause levels in this area makes this conclusion quite doubtful and this point is presented only as an analytical peculiarity of the data. With the development of the jet core near Athens the shaded tropopause break zone on the corresponding tropopause chart (fig. 4D) more nearly approximated the classical picture.

Following February 7, the trend of events changed and by 1500 GMT, February 9 (fig. 5B), the situation was reverting to that presented at the beginning of the period. The jet core between Flint and Dayton increased to values greater than 130 knots and that at higher levels in the Athens area subsided into a secondary wind maximum as on February 4. However, in this case highest wind speeds in the Nashville to Athens area were associated with the higher-level secondary wind maximum near 45,000 feet. The wind maximum near the same level in the Miami-Tampa area appears to be a reflection of another jet stream over Cuba.

With the strengthening of the strong jet core between Flint and Dayton the configuration of the tropopause changed to one quite similar to that observed on February 4 between Flint and Jacksonville. The weakening of the second jet core seems to be connected with changes in the high-level tropopause. A segment of relatively lower tropopause formed between Nashville and Tampa and the high-level tropopause which had conformed to the qualifications for tropopause identification on February 7 now existed as a level of significant stabilization[1] from Flint to Tampa with a southward extension as a definite tropopause through Miami. A similar situation appeared on the cross section for 1500 GMT, February 5 (not shown). The tropopause chart (fig. 5D) and the jet stream chart (fig. 5C) for 1500 GMT, February 9 exhibited features quite similar to those for February 4 (figures 3D and 3C). The shaded break zone in the northern Gulf of Mexico still persisted and the relatively stronger gradient of tropopause height reappeared in the Great Lakes region on the tropopause chart. The strong jet stream through the north central portion of the United States reasserted itself, again masking the subsidiary jet stream to the south on the jet stream chart. On February 4 the jet maximum through the southern Great Lakes was directly to the south of the area of lowest tropopause heights north of the Great Lakes. On February 9, the area of lowest tropopause heights was in the Dakotas and the jet maximum was located correspondingly to the south of this area.

6. TROPOPAUSE, JET STREAM, AND RAINFALL RELATIONS

Palmén and Nagler [5] have constructed a mean cross section in a case of approximately westerly flow over North America, and Riehl et al. [6] have used this cross section in a description of the synoptic structure of the jet stream. The cross sections presented here are remarkably similar to Palmén's mean cross section as described by Riehl. The "tropical" and "extratropical" tropopauses southward from the main jet stream core are well delineated on our cross sections, with temperatures, potential temperatures, and areal extent of the same general character as on the mean cross section. The "polar" tropopause, however, is not clearly delineated. The steepening of the tropopause height slope through the jet core and the lower tropopause to the north does have some resemblance to Palmén's cross section. (See discussion of figs. 3B and 3D.) Riehl also described the second jet, less intense than the first, between the "tropical" and "extratropical" tropopause leaves, also found on our cross sections (figs. 3B, 4B, and 5B). It therefore seems evident that the seemingly anomalous relationship of tropopause break zone and jet stream referred to in the introduction is not necessarily an unusual one. Throughout this period, tropopause leaves, or inversions not meeting the criteria for tropopause identification, were present as overlapping structures in the area of our cross sections. Since a tropopause level is arbitrarily defined, it follows that the position of the tropopause break zone depends only on the rigidity of the definition of tropopause level. No clear relationship between a jet core, which is based on definite wind observations, and a tropopause break zone, varying in position depending on tropopause definition, is therefore possible.

The precipitation area under consideration in this study can be related to these high-level features. Smith and Wilhelm [7] have investigated a situation of precipitation to the north of a front on the basis of low-level convergence factors. The consideration of high-level divergence is also of importance and this study has been restricted to the high levels.

An investigation at the University of Chicago [8] demonstrated, theoretically and by the analysis of vertical cross sections, the necessity for ascending motion immediately below and to the north of a zonal wind maximum and descending motion to the south. This suggested to Starrett [9] that the vertical motion postulated should tend to increase precipitation to the north and decrease it to the south of the jet stream. His observations showed that concentrations of precipitation activity did indeed exist in the vicinity of the jet stream as analyzed on the 300-mb. chart.

The high-level jet which was found through the Southern States on the cross sections and jet stream charts of this study can be related to the precipitation area under consideration in the same way. The great bulk of the precipitation occurred to the north of this jet where ascending motion could be inferred. However, it might be argued that the lower-level and stronger jet stream, which continued with varying intensity to the north of the precipitation zone throughout the period, indicated descending motion and thus should have inhibited precipitation. Riehl et al. [6] have developed a model illustrating the relation of the jet stream to pressure changes using changes in vorticity aloft, and inferred that precipitation will occur where the pressure is falling. His model showed that when a traveling wind maximum is moving in a straight westerly jet stream the right rear quadrant of the jet maximum is a favored area for pressure falls indicating ascending motion aloft. In an anticyclonically curved jet stream this quadrant is also a favored area for pressure falls and may be also in a cyclonically curved stream. The jet stream charts for the period indicated that the jet stream to the north of the precipitation area varied in intensity from day to day, and jet maxima could be detected moving eastward along the stream (see figs. 3C, 4C, and 5C).

The conclusion can therefore be made that as the individual jet maxima moved along the northern jet, the ascending motion to the north of the southern jet was alternately reinforced and opposed, and that it was during the periods of reinforcement that the precipitation occurred. Examination of the precipitation patterns on

[1] Significant stabilization is defined at NAWAC as a layer where the lapse rate is 3° C. per kilometer less than the lapse rate in the layer immediately below.

the surface maps throughout the period shows the intermittent character of the precipitation. At any given time precipitation was quite spotty and the precipitation areas could easily be tracked moving from west to east (see table 1 and figs. 3A, 4A, and 5A). The assumption that the precipitation was associated with the ascending motion which could be deduced between the two jet streams seems therefore tenable.

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